The Discovery of an Anomalous X-ray Pulsar in the Supernova Remnant Kes 73

G. Vasisht

California Institute of Technology, MS 105-24, Pasadena, CA 91125

E. V. Gotthelf[1]

NASA/Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

We report the discovery of pulsed X-ray emission from the compact source 1E 1841−045, using data obtained with the *Advanced Satellite for Cosmology and Astrophysics.* The X-ray source is located in the center of the small-diameter supernova remnant (SNR) Kes 73 and is very likely to be the compact stellar-remnant of the supernova which formed Kes 73. The X-rays are pulsed with a period of $\simeq 11.8$ s, and a sinusoidal modulation of roughly 30%. We interpret this modulation to be the rotation period of an embedded neutron star, and as such would be the longest spin period for an isolated neutron star to-date. This is especially remarkable since the surrounding SNR is very young, at ~ 2000 yr old. We suggest that the observed characteristics of this object are best understood within the framework of a neutron star with an enormous dipolar magnetic field, $B \simeq 8 \times 10^{14}$ G.

Subject headings: pulsars: individual (1E 1841−045) — stars: neutron — magnetic fields — (ISM:) supernova remnants: individual (Kes 73)

1. INTRODUCTION

In 1934, Baade and Zwicky published a prophetic paper making a phenomenological connection between supernovae (SNs), the core-collapse of massive stars, and the formation of neutron stars (then hypothetical); all purely on grounds of energetics. Decades later their conjecture was first vindicated by the discoveries of young pulsars in the Crab and Vela supernova remnants (SNRs), and now in a handful of other Galactic SNR.

Supernova remnants come in at least two distinct morphological types, i.e., shells and plerions (Weiler & Sramek 1988), and a majority are the result of core collapse in massive progenitors (the non-Type Ia SNs; van den Bergh & Tammann 1991). The Baade-Zwicky picture, in its simplest interpretation, is somewhat problematic. A majority of SNR appear not to contain either

---

[1] Also: Universities Space Research Association

central pulsars or pulsar plerions (as pulsars are beamed, plerions ought to be more commonplace than pulsars in the interiors of shells). The predominant "hollowness" of shell-remnants is ill-understood, and poses questions about the fate of *most* core collapses of massive stars. This conundrum is nowhere more apparent than in the studies of the youngest SNR, especially those of the historical supernovae (Strom 1994). Of the eight historical supernovae which have expanded into full-blown SNR, only the Crab Nebula has a pulsar. There is weak plerionic activity (but no beamed pulsars) in two others (SN 386 A.D. and SN 1181 A.D.; see Vasisht et al. 1996). It follows, therefore, that there is a need to give up our notions about the birth properties of young neutron stars, best typified by the Crab pulsar: fast rotation ($\lesssim 0.1$ s) and a dipole field strength clustered around 3×10^{12} G. That neutron stars may be born in a fashion drastically different from the Crab has become increasingly evident via recent X-ray studies. Preliminary evidence of this kind includes: the discovery of radio-quiet, cooling neutron stars (Vasisht et al. 1997 and refs. therein; Gotthelf, Petre & Hwang 1997) in SNR, the association of the exotic soft gamma-ray repeaters with young ($\sim 10^4$ yr old) SNR (see Thompson & Duncan 1995), and observations of magnetically dominated plerions (Vasisht et al. 1996). Also, the slowly-spinning ($P \approx 7$ s), anomalous X-ray pulsar (AXP) in the $\sim 10^4$ yr old SNR CTB 109, has been known for several years (Gregory & Fahlman 1980), although its nature is still widely debated (Mereghetti & Stella 1995; van Paradijs, Taam & van den Heuvel 1995; Thompson & Duncan 1996).

This *Letter* discusses 1E 1841−045, an unresolved Einstein point-source discovered near the geometrical center of the shell-type SNR Kes 73 (Kriss et al. 1985). The refined Rosat HRI location of the object is $\alpha_{J2000} = 18^h41^m19.2^s$ and $\delta_{J2000} = -04°56'12.5''$ ($\sim 3''$ at 90% confidence; (Helfand et al. 1994). The SNR shows no evidence for an extended plerionic core from either radio brightness morphology, polarization properties or spectral index distribution. This suggests that Kes 73, in spite its inferred youth, lacks a bright radio plerion. To date, no optical counterpart to the central X-ray source has been identified for 1E 1841−045. Herein, we present the discovery of ~ 12 s pulsed X-rays from 1E 1841−045 and argue that the source is young and unusual. In our companion paper (Gotthelf & Vasisht 1997; hereafter GV97) we present the results of imaging-spectroscopy of Kes 73 and the compact source.

2. OBSERVATIONS

Kes 73 was observed with the ASCA Observatory (Tanaka, Inoue & Holt 1994) on 1993, October 11-12, as a Performance and Verification (PV) target. Data were acquired by the two gas imaging spectrometers (GIS2 and GIS3) and collected with a photon time-of-arrival resolution of 488 μs in medium bit-rate mode and 64 μs in high bit-rate mode. We used data made available in the ASCA public archive, screened with the standard REV1 processing to exclude time intervals corresponding to high background contamination, i.e., from Earth-block, bright Earth, and SAA passages. An effective exposure of $\simeq 3.5 \times 10^4$ s was achieved with each detector and the on-source measured count rates for the GIS2 and GIS3 instruments were 1.55 (GIS2) and 1.66 (GIS3) counts

s^{-1}, respectively. Here, we concentrate on the GIS data exclusively and present data from the two Solid-state Imaging Spectrometers (SIS) on-board ASCA, in our companion paper (GV97), which reports on spectral and imaging results. We summarize the spectra pertinent to this paper below.

The spectrum of 1E 1841−045 is fit by an absorbed, soft power-law of photon index $\Gamma \simeq 3.0 \pm 0.2$ ($S_\nu \propto \nu^{-\Gamma}$). The foreground absorption towards Kes 73 is found to be $N_H \simeq 2 \times 10^{22}$ cm^{-2}, and is consistent with the kinematic distance estimate of 7 kpc (Sanbonmatsu & Helfand 1992). The power-law spectral normalization is found to be consistent with no long term spectral variation when compared to the count rates observed by Rosat HRI, $\simeq 0.02$ cps (Helfand et al. 1994). We deduce an unabsorbed model flux of 6.3×10^{-11} erg cm^{-2} s^{-1} (0.5 - 10.0 keV) yielding a source luminosity, $L_X \simeq 3.5 \times 10^{35} d_7^2$ erg s^{-1}; the SNR distance is $7.0 d_7$ kpc.

The long term temporal variability of 1E 1841−045 has been examined by Helfand et al. (1994) who found no concrete evidence for flux changes on the 10 year baseline between Einstein and Rosat. We examined the ASCA data for aperiodic variability by selecting source photons from a 5′ radius aperture and binning them on ~ 96 min (ASCA orbital period), 10 min and 1 min durations. The obtained light curves were χ^2 tested against a uniform model, but no evidence for significant variations on these time-scales was found.

A search for coherent pulsation from the central object was made by combining the two GIS high time resolution datasets ($t_s = 488$ μs). Photons were selected from the entire SNR region of $\simeq 5′$, centered on the compact object from (i) the entire energy band (0.5 - 10.0 keV) (ii) the hard band (2.5 - 10.0 keV). The photon time-of-arrivals were barycentered and binned with resolutions of 488 μs, 32 ms and 0.5 s. The barycentering and binning procedures were tested on a series of datasets of the Crab pulsar and PSR 0540−69. Fourier transforms on the entire datasets were performed at each time resolution, interesting periodicities were harmonically summed and later folded at the period of interest.

A significant high-Q X-ray modulation with no overtones is seen at a period $P \simeq 11.766684$ s ($f = 0.08498571 \pm 0.00000004$ Hz; see Figs 1 and 2). The modulation is obvious in all the above datasets and separately in either GIS on-source time series; it is not observed in off-source GIS data, making it unlikely to be an instrumental artifact. The period emerges with greatest significance in time-series which contain emission mainly from the central source (hard-band, 2.5 - 10.0 keV), and is not significant in the soft energy band between 0.5 - 2.5 keV, where the nebula is dominant. We suggest that the central object is weakly pulsed at 11.7667 s, possibly a neutron star spin period. The pulsed luminosity is $L_X \approx 5 \times 10^{34} d_7^2$ erg s^{-1}, and the modulation level is about 35% of the steady flux from the compact source after subtraction of the estimated contribution of the background and the SNR thermal component above 2.5 keV.

With a period in hand, we have reanalyzed the 18-ks of Rosat HRI data obtained between March 16-18, 1992 (Helfand et al. 1994), selecting the few ($\simeq 650$) source and background photons available from the vicinity of 1E 1841−045. We perform a conditional search in a small range of periods around 11.76 s using the folding technique (12 phase bins per fold); the resulting

periodogram is displayed in Fig 1b. We cautiously forward the suggestion of a peak-up at a barycentered period of 11.7645 s (4.0 σ; which is the expected significance given the HRI count rate and the ASCA derived modulation); the observed FWHM of the periodogram excess of $\lesssim 10^{-3}$ s is consistent with expectations, given the period and the time-span of the HRI observations. Also, the crest and trough in the HRI profile (Fig 2b) match those of the GIS profile quite well. A linear interpolation, assuming steady spin-down, gives a period derivative of $\dot{P} \simeq 4.73 \times 10^{-11}$ s s^{-1}.

3.   DISCUSSION

Our interpretation of 1E 1841−045 is that of a young neutron star that was born during a supernova that now forms the SNR Kes 73. The kinematic distance to the SNR of 6.7 - 7.5 kpc is consistent with its high foreground X-ray absorption, $N_H \simeq 2 \times 10^{22}$ cm^{-2}. The small shell radius ($R_s \simeq 4.7d_7$ pc), along with intense radio and X-ray shell emission are characteristics of a young supernova remnant. This notion is supported by our detection of a hot thermal ($kT \simeq 0.8$ keV) X-ray continuum in the shocked gas. Helfand et al. (1994) have argued that the SNR is likely to be in transition between free expansion and the adiabatic phases, whereby, the Sedov age of $\tau_s < 2500$ yr must be an upper bound. The SIS spectra show the enhancement of Mg over the species S, Si and Fe, along with possible evidence for highly absorbed emission from O and Ne in the 0.5-0.9 keV range (see GV97). During the course of their evolution, massive stars produce large quantities of O-group (O, Ne and Mg) which are ejected during the supernova (see Hughes et al. 1994). Hence, there is spectral evidence that Kes 73 is young and still ejecta dominated. On spectral grounds we also favor a Type II or Ib origin for Kes 73, i.e., from a massive progenitor. We consider it unlikely that the neutron star was born in an accretion-induced collapse of a heavy white dwarf (Lipunov & Postnov 1985).

The pulsar in 1E 1841−045 has common properties with the peculiar X-ray pulsar, 1E 2259+586 (Gregory & Fahlman 1980; Corbet et al. 1995), and the soft gamma-ray repeaters (Thompson & Duncan 1996). 1E 2259+586 is a 7-s spin rotator, and coincides with a $\gtrsim 10^4$ yr-old SNR (CTB 109). Much like 1E 1841−045, it has a soft X-ray spectrum best represented by a blackbody at 0.45 keV with a non-thermal tail with $S_\nu \propto \nu^{-3}$, and $L_x \simeq 0.5 - 1 \times 10^{35}$ erg s^{-1}. It has a history of nearly steady spin-down and no detected binary modulation (Iwasawa, Koyama & Halpern 1992), optical companion, or quiescent radio emission. There are four other X-ray pulsars, 4U 0142+614 (Hellier 1994; Israel et al. 1994), 1E 1048.1-5937 (Seward, Charles & Smale 1986), RXJ 1838−0301 (Schwentker 1994; possibly also associated with a $\gtrsim 10^4$ yr old SNR), and 1RXS J170849.0−400910 (Sugizaki et al. 1997) which have low luminosities ($L_X \sim 10^{35} - 10^{36}$ erg s^{-1}), periods of order 10-s that are steadily increasing, soft spectra and no detected companions or accretion disks. In all the above cases, spectra can be fit with soft power-laws with indices in the range 2.3 - 3.5 (Corbet et al. 1995). Collectively, these have been grouped into a class called the breaking X-ray pulsars (Mereghetti & Stella 1995) or alternatively, the anomalous X-ray pulsars (van Paradijs et al. 1995). We observe AXPs through a substantial distance in the Galactic disk

(with foreground columns densities $\sim 10^{22}$ cm^{-2}), which suggests that they are not commonplace.

The rotational energy of 1E 1841−045 is far too small to power its total X-ray emission of $L_X \sim 4 \times 10^{35} d_7^2$. The maximum luminosity derivable just from spin-down is

$$L_X \approx 4\pi^2 I \frac{\dot{P}}{P^3} \sim \frac{1}{2\tau_s} I (\frac{2\pi}{P})^2 \sim 10^{33} \text{ erg s}^{-1},$$

where I is the moment of inertial of the neutron star, and $\tau_s \sim 2 \times 10^3$ yr is the SNR age. The mechanisms for powering the X-rays could then be either (i) accretion from a high-mass X-ray binary (Helfand et al. 1994), a low mass companion (Mereghetti & Stella 1995), or a fossil disk (van Paradijs et al. 1995), or a merged white dwarf (Paczyncski 1990) (ii) intrinsic energy loss, such as initial cooling or the decay of magnetic fields in a magnetic neutron star (Thompson & Duncan 1996).

The strongest argument for accretion as the source of energy is that the inferred accretion rate is just that required if the NS is close to its equilibrium spin period P_{eq}, with a field $B \sim 10^{12}$ G typical for young pulsars (see Bhattacharya & van den Heuvel 1991)

$$P_{eq} \simeq 10 \text{ s } (\frac{B_d}{5 \times 10^{11} \text{ G}})^{6/7} (\frac{L_X}{10^{35} \text{ erg s}^{-1}})^{-3/7}.$$

However, only a pathological evolution scenario involving accretion could bring an energetic dipole rotator to its present rotation rate within $\simeq 2 \times 10^3$ yr. The strongest support for 1E 1841−045 as an accretor will be from future identification of an infra-red (large foreground $A_V \simeq 10$ mag.) companion or an accretion disk. As in the case of other AXPs an infrared counterpart may not be easily identified (Coe, Jones & Lehto 1994 and refs. therein). The pulsar has properties that may already preclude accretion as a power source: (i) high-mass neutron star binaries with a NS accreting from the companion wind sometimes go into low luminosity states with $L_X \sim 10^{35}$ erg s^{-1}, and have periods in the range 0.07 - 900 s. However, in general they display hard spectra $(0.8 < \Gamma < 1.5)$ and strong aperiodic variability on all time-scales (Nagase 1989). If the X-ray source is indeed a high mass X-ray binary then the inferred $\dot{P}$ could be the result of orbital Doppler effects. (ii) Neutron stars with disk accretion from a low mass companion or a fossil disk, with the latter having formed from SN debris or a Thorne-Zytkow phase (van Paradijs et al. 1995), should display similar accretion noise in the light-curve. (iii) Other AXPs show near steady spin-down on time-scales $10^4 - 10^5$ yr, although this is controversial (Baykal & Swank 1996; Corbet & Mihara 1997). The long term torque behavior of 1E 1841−045 will only be evident with future observations. iv) Finally, accretion models would have to be stretched in order to explain the slow rotation period (inside a young SNR) and its associated spin-down time-scale, $\lesssim 2500$ yr. First, it difficult for accretion torques to spin-down a pulsar to 12-s in $\sim 10^3$ yr from initial periods $P_i \lesssim 10^2$ ms unless, of course, the pulsar were *born a very slow rotator*, which is quite interesting in its own right. Secondly, if the pulsar were rotating near its equilibrium period, as in the Ghosh and Lamb (1979) scenario, the spin-down time of $P/2\dot{P} \sim 3900$ yr is inconsistent with the implied accretion rate, $\dot{M} \simeq 10^{-11}$ M$_\odot$ yr^{-1} (assuming the pulsar has a normal dipolar field $\simeq 10^{12}$ G); these usually lie in range $10^4 - 10^5$ yr.

A dipolar magnetic field vs. period scaling can also be obtained under the assumption that the neutron star is isolated, and has undergone conventional pulsar spin-down from torques provided by a relativistic wind, as in the Crab. For dipolar secular spin-down, the implied B_{dipole} is enormous,

$$P = 10 \text{ s } (\frac{t}{3 \times 10^3 \text{ yr}})^{1/2}(\frac{B_{dipole}}{10^{15} \text{ G}})(\frac{R}{15 \text{ km}})^2(\frac{M}{1.4 \text{ M}_\odot})^{-1/2}.$$

Such highly magnetized neutron stars (with dipolar field strengths $B \approx 10^{14} - 10^{15}$ G) or "magnetars" have been postulated by Thompson & Duncan (1995 and refs. therein) to explain the action of soft gamma-ray repeaters. Magnetars have magnetic flux densities that are a factor $\gtrsim 10^2$ larger than the typical $B \sim 10^{12}$ G fields supported by radio or X-ray pulsars and perhaps represent a tail of B-field distribution in NS. After birth, they spin-down too rapidly to be easily detectable as radio pulsars, assuming that they are capable of radio pulsar action at all. The dipole energy in the star's exterior, a small fraction of the total magnetic energy, exceeds the rotational energy of the NS after roughly $2B_{15}^{-4}$ yr, where $B = 10^{15}B_{15}$ G. Magnetism then quickly becomes the dominant source of free energy in an isolated magnetar.

The derived spin-down age of the pulsar ~ 3900 yr, is consistent with the SNR age (ages inferred from the estimator $P/2\dot{P}$ are larger than the true age as they measure linear spin-down).The equivalent dipolar field is $B_{dipole} \simeq 3.2 \times 10^{19} (P\dot{P})^{1/2} \approx 8 \times 10^{14}$ G. There is an intriguing possibility that the the pulsar in Kes 73 was born as a magnetar $\sim 2 \times 10^3$ yr ago, and has since spun-down to the long period of 11.7-s due to rapid dipole radiation losses. It could be unobservable as a radio pulsar due to period dependence of beaming (Kulkarni 1992); it is also possible the radio pulsar mechanism may operate differently or not at all above the quantum critical field, $B_{cr} \simeq 4.4 \times 10^{13}$ G. In a magnetar, the observed X-ray luminosity would be driven by the decay of the stellar B-field via diffusive processes, which set in at an age $\sim 10^3 - 10^4$ yr (Thompson & Duncan 1996; we assume that diffusion of field lines through the crust by Hall drift, and the core by ambipolar diffusion occur on time-scales $\tau_{Hall} \simeq 5 \times 10^8 B_{12}^{-1}$ yr and $\tau_{amb} \simeq 3 \times 10^9 B_{12}^{-2}$ yr, respectively; Goldreich & Reisenegger 1992). Magnetic field decay powers the star on average, at a steady rate of $(1/6t_d)R^3 B_{dipole}^2 \sim 10^{36}$ erg s^{-1} for the first decay time, $t_d \sim 10^3$ yr. Decay in the core is likely to keep the stellar surface hot via release of internal magnetic free energy, while crustal decay is likely to set up a steady spectrum of Alfvén waves in the magnetosphere which can accelerate particles to produce the soft non-thermal tail observed in the pulsar spectrum (GV97). Such a neutron star may in time ($\sim 10^4$ yr) display the soft gamma-ray repeater phenomenon (Thompson & Duncan 1996).

In conclusion, we reiterate that 1E 1841-045 is in our estimation a young (~ 2000 yr-old) neutron star spinning at an anomalously slow rate of $\simeq 11.8$-s, possibly with very strong torques on its rotation. The claim of rapid spin-down is based on a weak detection of periodicity in the archival Rosat HRI data, and needs to be urgently tested in future observations. Whatever the final consensus on 1E 1841−045, it is a most unusual and exciting object, the understanding of whose nature should make us rethink important aspects about the birth process of neutron stars as a whole.

REFERENCES

Baade, W. & Zwicky, F. 1934, Phys. Rev., 45, 138

Baykal, A. & Swank, J. 1996, ApJ, 460, 470

Bhattacharya, D. & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1

Coe, M. J., Jones, L. R. & Lehto, H. 1994, MNRAS, 270, 178

Corbet, R. H. D., Smale, A. P., Ozaki, M., Koyama, K. & Iwasawa, K. 1995, ApJ, 443, 786

Gregory, P. C. & Fahlman, G. G. 1980, Nature, 287, 805

Goldreich, P. & Reisenegger, A. 1992, ApJ, 395, 250

Gotthelf, E. V., Petre, R. & Hwang, U. 1997, ApJL, submitted

Gotthelf, E. V. & Vasisht, G. 1997, ApJL, submitted (GV97)

Helfand, D. J, Becker, R. H., Hawkins, G. & White, R. L. 1994, ApJ, 434, 627

Hellier, C. 1994, MNRAS, 271, L21

Hughes, J. P., Hayashi, I., Helfand, D., Hwang, U., Itoh, M., Kirshner, R., Koyama, K., Markert, T., Tsunemi, H. & Woo, J. 1994, ApJ, 444, L81

Iwasawa, K., Koyama, K. & Halpern J. P. 1992, ApJ, PASJ, 44, 9

Israel, G. L., Mereghetti, S. & Stella, L. 1994, ApJ, 433, L25

Kriss, G. A., Becker, R. H., Halfand, D. J. & Canizares, C. J. 1985, ApJ, 288, 703

Kulkarni, S. R. 1992, Phil. Trans. R. Soc. London, A, 341, 77

Lipunov, V. M. & Postnov, K. A. 1985, A&A, 144, L13

Mereghetti, S. & Stella, L. 1995, ApJ, 442, L17

Nagase, F. 1989, PASJ, 41, 1

aczynski, B. 1990, ApJ, 365, L9

Sanbonmatsu, K. Y. & Helfand, D. J. 1992, AJ, 104, 2189

Schwentker, O. 1994, A&A, 286, L47

Seward, F. D., Charles, P. A. & Smale, A. P. 1986, ApJ, 305, 814

Strom, R. G. 1994, A&A, 288, L1

Sugizaki et al. 1997, IAUC, 6585

Tanaka, Y., Inoue, H. & Holt, S. S. 1994, PASJ, 46(3), L37

Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255 (TD95)

Thompson, C., & Duncan, R. C. 1995, ApJ, 473, 322

van den Bergh, S. & Tammann, 1991, ARA&A, 29, 363

van Paradijs, J., Taam, R. E. & van den Heuvel, E. P. J. 1995, A&A, 299, L41

Vasisht, G., Aoki, T., Dotani, T., Kulkarni, S. R. & Nagase, F. 1996, ApJ, 456, L59

Vasisht, G., Kulkarni, S. R., Anderson, S. B., Hamilton, T. T. & Kawai, N. 1997, ApJ, 476, L43

Weiler, K. W. & Sramek, R. A. 1988, ARAA, 25, 295

Fig. − **1** (Top) A power spectrum of photons from both GIS cameras displayed in the range 11.75 - 11.78 s. Photons were selected from the hard-band (2.5 - 10.0 keV). The main peak near 11.766684 s is the putative pulsar period. The powerful side-lobe peaks are separated from the main peak by 0.00017 Hz, the ASCA orbital period. (Bottom) A periodogram of χ^2 vs. period of the HRI data, peaks up at roughly 4σ as is expected from the GIS profile (even though the energy range is different). The peak-up period is 11.7645 s. The total number of HRI counts for this was ~ 800. The search was done with twelve bins across the folding period.

Fig. − **2** (Top) A normalized folded profile of the GIS data (including background), with 12 bins of resolution, and a folding period of 11.7667 s. The profile is roughly sinusoidal, with about $\sim 35\%$ modulation (after accounting for the background). The start epoch of folding is MJD 4.9271609362×10^4. (Bottom) A normalized folded profile of Rosat HRI data, with 12 bins of resolution, at a folding period of 11.7645 s. The start epoch of folding is MJD 4.8697189×10^4.

Bin time: 0.9807   s

GIS

Normalized Amplitude

Phase

Bin time: 0.9804   s

ROSAT HRI

Normalized Amplitude

Phase

Bin time: 0.5000   s